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THE OPACITY OF THE UNIVERSE TO HIGH ENERGY PHOTONS \*

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Recently, Penzias and Wilson<sup>1</sup> at the Bell Telephone Laboratories have measured what appears to be extraterrestrial microwave radiation at 4080 Mc/s at an intensity corresponding to a "brightness temperature", or equivalent temperature of black body radiation, of  $3.5^{\circ} \pm 1.0^{\circ}\text{K}$ . Dicke, Peebles, Roll and Wilkinson<sup>2</sup> have interpreted this radiation as the expansion red shifted remnant of black body emission from a very early stage of the universe corresponding to an optically thick gas of electrons, positrons, photons, and nucleons at  $10^{10}^{\circ}\text{K}$ . During the expansion of the universe the radiation retains its black body character while being adiabatically "cooled" to its present value, supposed to be  $3.5^{\circ}\text{K}$ . The energy density of black body radiation at this temperature is  $\epsilon \approx 1 \text{ eV/cm}^3$ , while the mean photon energy is  $\langle \epsilon \rangle \approx 10^{-3} \text{ eV}$ . The number density of these photons in the universe is then very large:  $n \approx 10^3 \text{ photons/cm}^3$ . The presence of these cosmic photons has already been shown<sup>3</sup> to have possible observable effects due to Compton collisions with relativistic electrons associated with cosmic radio synchrotron radiation.

The purpose of the present paper is to point out another effect of the presence of these photons. This is the effect of absorption of high energy photons traversing cosmic distances due to electron-positron pair production in photon-photon collisions. Here we give the essential results of the effect related to experiments on high energy cosmic photons; full details will be given elsewhere. The basic process involved is well known<sup>4</sup>; it is just the reverse of direct  $e^{+} - e^{-}$  two photon annihilation. The pair production process has a threshold, since in the center of mass system of the photons the total photon energy must be greater than  $2m_e (c=1)$ . In

fact the cross section for the process is a maximum near threshold corresponding to  $\epsilon E \gtrsim m_e^2$ , where  $\epsilon$  and  $E$  are respectively the low and high energy photon energies in the lab system. Thus, for  $\epsilon \sim 10^{-3}$  eV, we see that the process is <sup>most</sup> important for energies  $E \gtrsim 3 \times 10^{14}$  eV of the high energy photons. Moreover, since the cross section for the process is <sup>4</sup>  
 $\sigma \sim r_0^2 \sim 10^{-25}$  cm ( $r_0$  is the classical electron radius), the mean free path for the high energy photons is  $\lambda \sim (n \sigma)^{-1} \sim 10^{22}$  cm, roughly the size of the Galaxy. This is very significant, since during the past few years there have been some attempts <sup>5,6</sup> to detect ultrahigh energy primary cosmic photons of energy  $\gtrsim 10^{14}$  eV. In these experiments the procedure is to look for extensive air showers (EAS) containing an abnormally low number of muons, which would indicate that the showers were initiated by an electromagnetic rather than a nuclear process. In fact both the Polish group <sup>6</sup> operating at sea level and the American-Bolivian-Japanese group <sup>5</sup> operating at high altitude (5200 m) on Mt. Chacaltaya in Bolivia have indeed reported the occurrence of muon-poor or muon-less showers at a frequency about  $10^{-3}$  of the number of ordinary showers at primary particle energies of  $10^{14}$  eV. In addition, significantly, the arrival directions of the low muon showers shows no anisotropy, indicating that the (assumed) photons are of extragalactic origin.

Attenuation of cosmic photons by the  $\gamma + \gamma' \rightarrow e^+ + e^-$  process was first considered by Nikishov <sup>7</sup> for absorption by ( $\sim$  eV) optical stellar photons; he showed that the effect can be appreciable for high energy photons of energy  $\sim 10^{12}$  eV. Nikishov's formulation can be made more general to give the absorption probability from interaction with an (undiluted) black body photon gas at any temperature  $T$ . One can easily show (details given elsewhere) that the absorption probability per unit photon path length for

photons of energy  $E$  is ( $\hbar = c = 1$ )

$$\frac{d\tau_{\text{abs}}}{dx} = \frac{\alpha^2}{\pi\hbar} \left( \frac{kT}{m} \right)^3 f(\nu), \quad (1)$$

where  $\alpha^{-1} = 137$ ,  $\Lambda (= \pi^{-1})$  is the electron Compton wavelength,  $\nu = m^2/EkT$ , and  $f(\nu)$  is a function computed essentially from an integration over angles and energies of the low energy black body photon spectrum. It has the asymptotic forms

$$\begin{aligned} & (2) \quad f(\nu) \rightarrow \begin{cases} (\sqrt{\pi}/2) \nu^{1/2} e^{-\nu}, & \nu \gg 1 \\ (\pi^2/3) \nu \ln(0.117/\nu), & \nu \ll 1 \end{cases} \\ & (3) \end{aligned}$$

and has a maximum value  $\sim 1$  at  $\nu \sim 1$ . We give the absorption probability as a function of energy for  $T = 3.5^\circ \text{K}$  in Fig. 1. It is seen that the absorption probability  $d\tau_{\text{abs}}/dx$  is greater than the reciprocal of the "Hubble radius"  $R_H$  ( $\sim 10^{28}$  cm) or "radius of the Universe" for  $10^{14} < E < 10^{22}$  eV. For photons in this energy range the absorption optical depth to the edge of the Universe would be greater than unity. That is, we could "see" only out to a distance  $d \sim (d\tau_{\text{abs}}/dx)^{-1}$  in the Universe. We see from Fig. 1 that for  $E = 10^{16} - 10^{17}$  eV  $d$  is only about  $10^{23}$  cm. This has an important consequence for the experiments on muon-poor EAS. If as it seems, the (supposed)  $\sim 10^{14}$  eV photons are of extragalactic origin, they must be coming from sources at distances  $< 10^{26} - 10^{28}$  cm. However, recently<sup>8</sup> the experimental group on Mt. Chacaltaya have been accumulating data on larger showers containing  $10^7 - 10^8$  particles corresponding to

primary energies of  $2 \times 10^{16} - 2 \times 10^{17}$  eV. Of the 2000 of these showers detected so far, none have been found to be muon-poor. Of course, more showers would have to be observed for the statistics to be significant. Our prediction is that no muon-poor showers corresponding to primary energies of  $2 \times 10^{16} - 2 \times 10^{17}$  eV will be found. For, as is seen from Fig. 1, the photon absorption probability is high for these energies. In fact, if there does exist a primary high energy cosmic photon flux, we would predict that its spectrum will show a cut-off at about  $10^{14}$  eV due to the rapid increase in photon absorption for energies above this value.

Unfortunately, there is no way of distinguishing between a photon-initiated and electron-initiated shower. However, due to Compton scattering energy losses from collisions with the low energy thermal ( $3.5^\circ\text{K}$ ) photons, the electron path length for energy loss would be only  $-E(dE/dx)^{-1} \sim 4 \times 10^{21}$  cm for  $E \sim 10^{14}$  eV. Thus, under these conditions electrons of this energy could not possibly exist in abundance either in intergalactic space or in the Galaxy. In the absence of the thermal photons the principal energy loss process in the Galaxy is synchrotron radiation. If the mean galactic magnetic field is  $\sim 10^{-6}$  gauss, the energy loss path length is  $\sim 10^{23}$  cm but the Larmor radius is only  $\sim 3 \times 10^{17}$  cm so that motion of the high energy electrons would be primarily along the field lines. Electrons of energy higher than  $10^{14}$  eV could not traverse the Galaxy without losing their energy. Thus, we see that a cosmic electron spectrum could also show a cut-off at energies around  $10^{14}$  eV, and an observation of a cut-off in the energy spectrum of particles producing muon-poor showers would not prove that they were initiated by photons. However, if the  $3.5^\circ\text{K}$  cosmic blackbody radiation were proven conclusively to exist, the cut-off in the electron spectrum would have to be at  $E \lesssim 10^{13}$  eV - about an order of magnitude lower than that for cosmic photons.

One final point should be emphasized: If there does exist a truly cosmic high energy photon spectrum, the shape of the cut-off edge due to photon-photon collisions would depend on the structure of the universe at great distances. Because of this, there exists the possibility of observationally testing cosmological models by measuring the high energy photon spectrum in the vicinity of the cut-off. This amounts to measuring in detail the muon-poor shower frequency as a function of shower size and would require a long range experimental program. Clearly, the results of such a program could be of great importance.

We have benefited from conversations and communications with H. Bradt, J. E. Felten, and P. Goldreich.

FOOTNOTES

- <sup>1</sup> A. A. Penzias and R. W. Wilson, *Astrophys. J.* 142, 419 (1965)
- <sup>2</sup> R. H. Dicke, P. J. E. Peebles, P. G. Roll, and D. T. Wilkenson, *Astrophys. J.* 142, 414 (1965)
- <sup>3</sup> J. E. Felten, "Inverse Compton Radiation from Intergalactic Electrons and Cosmic Blackbody Photons", submitted to *Phys. Rev. Letters*.
- <sup>4</sup> Cf. J. M. Jauch and F. Rohrlich, Theory of Photons and Electrons (Cambridge, Mass.: Addison-Wesley Publishing Co. 1955)
- <sup>5</sup> K. Suga, J. Escobar, G. W. Clark, W. Hazan, A. Hendel, and K. Murakami, *J. Phys. Soc. Japan* 17, Suppl. A-III, 128 (1962), see also Proc. Jaipur Conf. on Cosmic Rays.
- <sup>6</sup> R. Firkowski, J. Gawin, R. Maze, and A. Zawadski, *J. Phys. Soc. Japan* 17, Suppl. A-III, 123 (1962), see also Proc. Jaipur Conf.
- <sup>7</sup> A. I. Nikishov, *Soviet Physics J. E. P. T.* 14, 393 (1962); see also P. Goldreich and P. Morrison, *ibid.* 18, 239 (1964).
- <sup>8</sup> H. Bradt, private communication.

FIGURE CAPTION

Fig. 1 Absorption probability per unit path length as a function of energy for high energy photons traversing a black body photon gas at 3.5 °K by means of the process  $\gamma + \gamma' \rightarrow e^+ + e^-$ . The absorption probability for interaction with a black body photon gas at other temperatures may be computed with the help of this curve and eq. (1).



